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Low-temperature convective drying of apple cubes

Ivan Zlatanović [a,*], Mirko Komatina [b], Dragi Antonijević [c]

[a] Department of Agricultural Engineering, University of Belgrade, Faculty of Agriculture, Nemanjina 6, 11080 Belgrade, Serbia
[b] Department of Thermomechanics, University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia
[c] Singidunum University, Faculty of Applied Ecology, Požeška 83, 11000 Belgrade, Serbia

HIGHLIGHTS

► An experiment for low-temperature convective drying of apple cubes is conducted.
► A convective laboratory scale dryer with full air recirculation is built.
► The experiments are in ranges: 35–55 °C, 10–30% RH, 1–2 m/s, cube size 10 and 13 mm.
► The analysis of the results enabled derivation of drying parameters correlations.
► Different combinations of drying parameters can produce similar drying effects.

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ABSTRACT

The paper presents results of an experimental investigation of convective drying of *Idared* apple in full recirculation laboratory scale dryer. The experiments were conducted with cube-shaped apple samples (side length 10 and 13 mm), without pre-treatment. The parameters of air stream over the tray with samples were fully controlled and adjusted in several sets of experiments, while always remaining in the following ranges: temperature 35–55 °C, relative humidity 10–30%, velocity 1–2 m/s. The drying kinetics of the apple samples was recorded, the results were analyzed and compared to the existing drying models. The analysis of the experimental results enabled derivation of correlations between drying parameters in a form $k = f(T,\mathrm{RH})$, within Henderson & Pabis drying model $\mathrm{MR} = a\exp(-k\tau)$, as well as the calculation of effective moisture diffusivity during the process.

1. Introduction

Wide ranges of laboratory scale dryer equipment, which have great similarity to UOP-8 model (tray dryer, *Armfield UK*) were used in different fruit drying experiments. The uses of previously mentioned UOP-8 model in their studies were reported by the authors [1] and [2]. Depending on the particular experiment issues only minor modifications of this type of dryer can be noted. For example, in experiment [3] with temperature monitoring and experiment [4] with temperature and weight monitoring, the dryers are placed in vertical position. The tunnel dryer used in the apple drying experiments [5] was additionally equipped with plastic tubes for air stream routing. In experimental setup [6] the dryer was microwave-assisted and in Ref. [7] dryer was assisted with components for infrared drying, but all other components remained the same. Similar approach was retained in laboratory dryer [8] and cabinet dryer used in Ref. [9] that have the same principle of operation but different arrangement of internal components. Experimental measurements [10] and [11] are conducted on home-made dryers with identical arrangement of components like in UOP-8 dryer model. Experiments were usually conducted with possibility of drying air temperature and velocity variation, but mainly without drying air relative humidity (RH) variation. These types of installations usually use ambient air as hot drying air that has been previously heated with electric heaters. Drying air RH only depends on initial temperature and humidity values of ambient air and it is not often considered as important drying parameter [12]. The exception is made with experiments conducted on heat pump supported convective dryers that have the technical ability to control and vary drying air RH values by operating with full or partial air recirculation. According to Ref. [13] heat pump condenser and evaporator are often sufficient components to perform the drying process. Better control of drying parameters could be achieved in systems with additional components [14] like electric air heaters and systems with partial air recirculation [15]. Only few authors consider drying air RH as important drying parameter,

* Corresponding author. Tel.: +381 63 401611; fax: +381 11 3169909.
E-mail addresses: ivan@agrif.bg.ac.rs, ivan.zlatanovic@gmail.com (I. Zlatanović).

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by taking it into account through the modeling process of system components [16] and system performance [17], or by analyzing drying kinetics [18] and interconnection between used drying parameters [19]. The experimental research [20] shows that the more precise control of the drying process parameters can be achieved if there is air temperature and humidity control of entire room (air conditioned room) where drying chamber is placed. But even then RH is often ignored and kept constant [21]. The lack of entire ambient control is that this way of achieving precise drying parameters is possible only within laboratory conditions [22]. In general, all laboratory dryers with complete or partial drying air recirculation [23] have potential for precise regulation of initial drying air RH values with insignificant amount of water injected into the process. According to Ref. [24] the benefit of the drying systems with full recirculation is highly achieved thermal efficiency. Removal of the water in its liquid state rather than its vapor state allows the latent heat of vaporization to be captured and only small amount of sensible heat to be lost. Energy efficiency analysis [25] of air cycle heat pump dryers and exergy analysis [26] of heat pump dryer shows that this type of heat recovery by drying air recirculation process could increase the energy efficiency of the process. With appropriate system optimization [27] up to the 40% of consumed energy can be saved. Literature review [28] and [29] of heat pump drying systems shows that any combination of the recirculation process within adequate heat pump system is desirable from the energy efficiency point of view. Analysis shows that up to 60–80% of conventional dryer consumed energy could be saved [30], with heat pumps of new generation implementation. However, some authors think that full air recirculation in systems with heat pump support is desirable but not exclusive [31]. Additional savings could be achieved by using renewable energy [32] or alternative energy sources such as waste heat from industrial processes [33]. The study performed on hybrid drying system [34] confirms the importance of improving heat recovery to improve the performance of heat pump-assisted drying systems. According to Ref. [35] heat pump systems will greatly improve energy efficiency if they include multiple energy sources, multiple heat sources and multiple functions to significantly improve energy utilization.

The studies of drying kinetics which omit some of the effective drying parameters could not be easily repeated because of the arbitrary values of those parameters. Previously mentioned UOP-8 like laboratory dryers take the drying air from the room in which they are located and use the same room for the exhaust moist air. Therefore, air humidity in the room during the experiment increases which results in variations of relative humidity that enters the dryer. Unlike these studies, this study uses full air recirculation to provide better control of the main drying parameters and to minimize impact of the surroundings (on the drying process). Experimental results are frequently discussed through their comparison with existing drying curve models or with other experimental results in order to find the one with minimum deviation. The evaluation of the relevance of specified drying air parameters for a drying process is rare in literature and therefore the present study is directed toward quantification of influence of drying air parameters for the process of convective drying of apple cubes.

2. Materials and methods

Apples (var. *Idared* [37]) were used in the experiments. This variety of apple takes first place with approx. 50% of Southeast Europe region apple production and third place with 8.6% of annual European Union apple production. It is available on the market up to 200 days/year, thanks to the excellent storage properties.

The usual shapes of the final product of dried apples are: quartered apple pieces, ring apple pieces, apple slices and diced apples. Cube shape is chosen because of the simplicity and solvability of the diffusion model equations [38]. The side dimensions of 10 and 13 mm are chosen from the range between 6 and 20 mm, that is a normal range for this shape of the material widely used in literature. For example, 20 mm apple cubes were used in experiments [1], 8 mm cubes in Ref. [3], cube side dimensions in range 6–18 mm in Ref. [8], and rectangle samples with side dimensions in range 5–38 mm in Ref. [11]. The experiments described in this paper use two sizes of cube-shaped apple dried material, but also it is possible to determine all relevant drying parameters and correlations for other material shapes and dimensions.

For samples preparation, apples were washed, peeled and cut into cubes with 10 and 13 mm side dimension. The samples were put in thin-layer on the 240 $\times$ 200 mm tray with net weight of 0.71 kg. The initial moisture content of apple cubes was determined using the oven-drying method [3] with repetition in order to assure accurate initial moisture content average values. The initial moisture content of the samples was found to be 89.5 $\pm$ 0.3%, with initial moisture ratio of 8.55 kg water/kg dry matter.

2.1. Experimental apparatus

Convective laboratory scale dryer with possibility of full drying air recirculation was designed and built in order to achieve and measure all relevant drying process parameters. This dryer is capable for accurate control of all parameters of convective air stream relevant for its ability to absorb moisture from the surface of dried material (agent air drying potential [36]).

Laboratory scale convective tray dryer (Fig. 1) operates with full recirculation of drying air and allows control of drying air RH. It consists of a floor standing horizontal and vertical tunnel section and duct section for loop closure. Water heater (WH) used for air heating is positioned at the top of the vertical tunnel section above the tray section (TR) that stands on digital weight indicator (DWI). Water cooler (WC) used for air cooling is positioned at the bottom of the horizontal tunnel section, just below the by-pass (BP) line. Water condensed on WC surface use gravity force to get out of the system and it is collected in graduated glass cylinder (GC). Fan is located in the horizontal tunnel section and it provides desired drying air velocity. Downstream of the fan sprinkler (SP) is positioned in intensive turbulent flow airstream for better water drop dispersion. Air flow through BP and WC is regulated with by-pass damper (BPD) and water cooler damper (WCD) manually. Fan speed is regulated with electric motor frequency control unit.

Measurements of drying air velocity, temperature and relative humidity were performed at positions 1 to 5 (Fig. 1). Measurements of ambient air properties were performed at position 6 (Fig. 1). All other parameters related to dryer components control were measured at following positions (Fig. 1): A, B, C and D – water flow and temperature at WH and WC inlet/outlet connections; E – sample weight during the drying process; F – removed water volume; G – electric motor parameters (current frequency); H – injected water volume. The measurement equipment used in experiments has the following accuracies: temperature measurement: $\pm$0.175 °C, air relative humidity measurement: $\pm$1%, drying air velocity measurement: $\pm$0.01 m/s, weight measurement: $\pm$0.001 kg, measurement: $\pm$5 cm^3, current frequency measurement: $\pm$0.01 Hz.

2.2. Experimental design

Each experiment (E_n) involves monitoring and recording of all the relevant parameters during one invariable drying regime (T, RH, w) of apple samples with single cube size (L). In total, two sets of experimental measurements were conducted for each of the dimension material (10 and 13 mm). Achieving the required