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Research Paper

Non-uniformity investigation in a combined thermal and microwave drying of silica gel

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HIGHLIGHTS

- Uniformity in combined thermal and microwave (CTMW) dryer was analyzed.
- Local temperature and moisture of silica gel were determined to analyze uniformity.
- The effects of microwave power and temperature of the hot air on drying uniformity were investigated.
- The uniformity changes in the horizontal direction of the drying cavity were not obvious.
- The temperature gradient of silica gel between the layers can reach 5 °C.

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ABSTRACT

Local temperature and moisture were determined to analyze the uniformity in vertical and horizontal planes in a combined thermal and microwave (CTMW) drying chamber. Furthermore, the effects of microwave power and temperature of hot air on drying uniformity were also investigated. It could be concluded that the dried silica gel in the center area of the drying chamber obtained the highest drying rate and temperature, followed by the silica in the outermost and the middle portions. The dehydration difference of the three layers decreased with the drying time, whereas the drying uniformity increased. Overall, the change in uniformity in the horizontal direction of the drying cavity was not obvious, and the temperature and moisture content gradients mainly occurred in the vertical direction. The temperature gradient between the layers reached 5 °C. As the hot air temperature and microwave power increased, the drying rate improved and the drying uniformity decreased.

1. Introduction

Microwave (MW) heating offers several distinct benefits, including increasing throughput and higher energy efficiency, but its intensity and penetration depth depend on the physical and dielectric properties of the substrate and can vary with temperature, frequency, composition and shape. With bio-products characterized by low thermal conductivity, MW heating may exhibit a certain non-uniformity in the temperature distribution, leading to local overheating or even run-away loci [1–3], which not only damages the quality of the food due to hot spots, but also raises the issue of food safety as pathogenic microorganisms may not be destroyed in cold spots [4].

Heating uniformity in microwave processing can be improved in different ways. Currently, modification of relevant food or package parameters to optimize the heating uniformity are important in food product development [5–8]. Microwave oven designs such as rotating turntables in household microwave ovens, moving conveyor belts in industrial appliances and mode stirrers often result in uniformity [4]. However, due to their limited response in process performance, MW treatments have been renovated from MW irradiation alone to hybrid processing [9–12]. Combined thermal and microwave (CTMW) drying has been proposed for over a decade. Volumetric heating (caused by microwave power) drives moisture from the product's interior toward the surface, where it is removed by the surrounding heated air currents. This coupled drying method has been shown to be a promising technology for reducing drying times and providing the desired temperature profiles needed for specific food processes [13–19].

To date, CTMW dryers have been successfully operated only on a small, experimental scale [20–22]. Attempts to make such dryers for industrial-scale use have been limited. In a laboratory-scale dryer, the volume of the cavity is small, and in such a small space, the non-uniformity of the microwave distribution is not notable. However,

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the non-uniformity of the microwave distribution becomes a serious problem in an industrial-scale dryer. To overcome this difficulty, the main strategies available for use by most researchers are to move or float the drying materials around the cavity with convective air [21–23]. This strategy, however, leads to difficulties in managing the structure of the coupled dryer for large industrial-scale cavity. Moreover, most of the research on combination CTMW heating has been conducted in the context of microwave convection drying characteristics and simulations [24–26], in which the spatial uniformity of heating and drying was not deemed to be the key parameter and was therefore seldom reported. Most of these studies have treated the food to be dried as one lump sum so that spatial information from different points in the cavity was not recorded. Measurements of temperature and moisture distributions in the cavity during CTMW drying could capture the spatial and temporal heating patterns, and such information could provide valuable insights into the nature of combination heating. Such information could enable more effective designs for coupled CTMW dryers. However, no such study has been recorded in the literature.

In this study, a novel CTMW dryer was designed and fabricated. In particular, a new strategy was tested that involved varying the distributions of microwaves and allowing the dried materials to remain motionless in the cavity. Using silica gel as the experimental material, changes in the temperature and moisture of samples in specified zones of the dryer plates were measured to evaluate the uniformity of heating and drying. The advantages of the combined CTMW method were apparent in the results, which demonstrated a more convenient means of managing temperature with greater uniformity in the microwave distribution. Such results raise the possibility of building CTMW dryers on a large or industrial scale.

Therefore, the objectives of this study were (1) to determine local temperature and moisture in horizontal and vertical planes in the drying chamber using silica gel in an experimental test and (2) to explore the effect of MW power and the temperature of hot air on drying uniformity.

2. Materials and methods

2.1. Materials

Silica gel (Model 10018360, National Medicine Group Chemical Reagent Co., Ltd., China) was used as the test material. Before the experiment, the gel was saturated with water vapor until the moisture content reached to 27.2% (w.b.). Silica gel has strong adsorption affinity for water vapor in air. Dry silica gel is blue, and wet silica gel shows different colors that depend on the quantity of crystallization water [29].

2.2. Drying equipment

The pilot-scale CTMW dryer was designed by the authors (Fig. 1a). The dimensions of length, width and height of the multimode rectangular cavity are 540 × 400 × 550 mm, and the volume is 115 L. There is a certain interval of 10 cm between the three trays. Each layer tray had an area of 0.17 m^2 and was made of a glass fiber mesh grid. The heating feasibility of a material via MW irradiation depends on dielectric properties (or permittivity) [3]; trays with a low dielectric constant almost do not absorb MW energy and ensure it was absorbed by the working samples and allow air and water vapor to pass through them. The hot air production port was located in the back of the drying chamber (or cavity). This port consisted of a centrifugal fan, an electric heating tube and a circulating air duct. The hot air was cycled through the drying chamber, and the high humidity air was discharged through an air vent at the top of the dryer cavity. The size of the air vent could be adjusted to change the air velocity. The hot air temperature could be changed within a range of 40~120 °C, and the air velocity varied in the range of 0.3~1 m/s. The composition and structure of the microwave power feed port is shown in Fig. 1b. This structure consisted of a magnetron, a waveguide and an (electric and magnetic) EM field mode stirrer. The microwave power transmitted by the magnetron was transferred through the waveguide to a metal tray connected to the drying chamber. The metal mode stirrer was installed at the outlet of the waveguide and rotated by a motor at 25 rpm. This mode stirrer device mechanically changed the emission conditions and periodically disturbed the regularity of the EF (or electric field). The working frequency of the microwave was 2450 MHz, and a digital inverter solution for which the energy output could be adjusted from 100 to 1500 W by step-less high voltage regulation for the microwave oven (Model: WepeX 1600A, Shenzhen Mebmeet Electrical Technology Co., LTD, Shenzhen, China) was adopted. The nominal power is the actual power output of the microwave inverter indicated by its control panel (Model: WepeX-C1, Shenzhen Mebmeet Electrical Technology Co., LTD, Shenzhen, China). All times were measured using a PC-based stopwatch. Before the experiment, the hot air heater was opened for at least 30 min.

2.3. Determination and analysis methods

2.3.1. The absorbed power

A calorimetric method was adopted to evaluate the nominal MW power P supplied to the sample.

One liter of tap water was weighed in a beaker, and its initial temperature was read by a K-type thermocouple. Following a full-time exposure to MW, the water was briefly mixed, and its temperature was read again to determine P.

The absorbed power was determined by the following relationship [1]:

$$p = C_P m \frac{\Delta T}{t}$$

According to the calculation, nominal powers of 500 W, 600 W and 700 W in the experiments correspond to actual absorbed powers of $490 \pm 5\ W$, $588 \pm 10\ W$, and $685 \pm 15\ W$, respectively.

The humidity ratio:

$$MR = \frac{M - M_e}{M_0 - M_e}$$

M——The mass of the samples after t minutes of drying time
M_0——The initial mass of the sample
M_e——The quality when the sample has moisture balance

2.3.2. Determination of drying uniformity

The water uniformity K_a was used to describe the drying uniformity of each dish: $K_a = (x - \Delta x)/x \times 100\%$

x ——The average value of dehydration in all trays (g)
Δx ——Variance of dehydration in all trays (reflecting water dispersion degree for dehydration in all dish)
K_a values closer to 100% indicate a greater degree of uniform drying.

2.3.3. Determination and analysis by Infrared thermal imaging

An FLIR T440 infrared thermal imager (FLIR Systems company, USA) was preheated for 10 min before each test. Infrared emissivity was set at 0.95, and the detection distance was kept at a distance of 50 cm. Detected data were analyzed by FLIR Reporter software. This method of determining the temperature only allows for measurements of surface temperature.