Drying characteristics of ultrasound assisted hot air drying of *Flos Lonicerae*

Yunhong Liu · Yue Sun · Shuai Miao · Fang Li · Denglin Luo

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Abstract Ultrasound assisted hot air drying of *Flos Lonicerae* was investigated in this study. The effects of drying parameters such as ultrasonic radiation distance, ultrasonic power and drying temperature on drying characteristics were discussed. The results showed that ultrasound application has positive and significant effects on hot air drying. Shortening ultrasonic radiation distance is beneficial to improve both ultrasonic energy efficiency and drying rate. Higher ultrasonic power had more positive and significant effects on drying rate. The influence of ultrasound power on drying rate decreased along with the decrease of moisture content during drying process, especially at low ultrasound powers. The increase of drying temperature significantly caused the reduction of drying time. D_{eff} values ranged from 5.05×10^{-11} to $20.33 \times 10^{-11} \text{ m}^2/\text{s}$ in ultrasound assisted hot air drying of *Flos Lonicerae*, and increased with the increase in drying temperature and ultrasonic power. The corresponding activation energy values ranged from 28.90 to 36.05 kJ/mol, and decreased with the increase in applied ultrasonic power. Therefore, ultrasound assistance is a helpful and promising method to enhance hot air drying process.

Keywords Ultrasound · Hot air drying · *Flos Lonicerae* · Drying characteristics

Introduction

Hot air drying (HAD) is one of the most traditional dehydration methods for preserving foodstuffs (Stakic and Tsotsas 2005). However, this drying method involves several disadvantages, such as its low energy efficiency and lengthy drying time during the falling rate period (Maskan 2001; Yongsawatdigul and Gunasekaran 1996). Moreover, unexpected quality degradations including undesired food flavor, enzymatic browning and vitamin degradation are easily produced. The degradation of product quality is linked to high temperature and long drying time of HAD (Gamboa-Santos et al. 2014). The application of new or innovative techniques that can increase drying rate and enhance product quality may overcome some limitations of traditional HAD process.

Among emerging technologies, ultrasonic dehydration is very promising to be applied in HAD. In comparison to other technologies such as microwave and infrared radiation, the effects of ultrasound on kinetics are based on mechanical mechanisms more than on heating effects, which lead to a shorter drying time without heating the product to any significant degree (Puig et al. 2012). Acoustic energy produces oscillating velocities and microstreaming at the interfaces which may break the bonding of water molecules and product surface and minimize diffusion boundary layer thickness (Gallego-Juarez et al. 1999). A series of alternative compressions and expansions can be produced when ultrasonic waves travel through the material, and this alternating stress can be higher than surface tension of the moisture inside the capillaries of the material and can create microscopic channels which may improve water removal additionally (Mulet et al. 2003). Moreover, acoustic waves may produce cavitation which may be beneficial for the removal of strongly attached moisture (Mulet et al. 2003). Therefore, all the effects produced by ultrasound could affect external and internal resistance during ultrasound assisted hot air drying (UHAD), and

Y. Liu (✉) · Y. Sun · S. Miao · F. Li · D. Luo
College of Food and Bioengineering, Henan University of Science and Technology, 263 Kaiyuan Road, Luolong district, Luoyang 471023, China
e-mail: lyunhong@hotmail.com

increase dewatering rate as a result (Garcia-Perez et al. 2007). The positive effects of ultrasound on HAD process has been proven in the drying of several fruits and vegetables, such as apple (Sabarez et al. 2012), red bell pepper (Schossler et al. 2012), eggplant (Puig et al. 2012), orange peel (Ortuño et al. 2010), carrot, persimmon and lemon peel (Garcia-Perez et al. 2007).

Flos Lonicerae, the dried flower bud of *Lonicera japonica* Thunb. (*Caprifoliaceae*) and also known as *honeysuckle* or *Jin Yin Hua*, is a traditional Chinese medicine herb commonly used in Asia, especially in China. It is generally used for the treatment of sores, carbuncles, furuncles, swelling and affections caused by exopathogenic wind-heat or epidemic febrile diseases at the early stage (Lee et al. 1998; Peng et al. 2000). Essential oil, saponins, terpenoids, flavones and phenolics as the main components were isolated and identified (Peng et al. 2000; Shang et al. 2011). Among of them, essential oils and chlorogenic acid were thought as the active compounds of *Flos Lonicerae* (Committee for the Pharmacopoeia of PR China 2010; Shang et al. 2011). The color of *Flos Lonicerae* is easily browning and polyphenol compounds inside such as chlorogenic acid are easily degraded, mainly because of enzymatic oxidation reaction, hence it is difficult to preserve *Flos Lonicerae* in fresh form. So *Flos Lonicerae* should be dried immediately after harvesting to avoid perishing and to keep effective components inside as much as possible. The most common methods for the drying of *Flos Lonicerae* are oven house drying and HAD (Ji and Zhu 2008; Peng et al. 2006; Zhang et al. 1999), yet the stamens and pistils inside *Flos Lonicerae* are difficult to dehydrate entirely, mainly due to their great internal diffusion resistance. So, some assisted techniques should be applied to strengthen internal moisture diffusion rate of *Flos Lonicerae*. Because of its excellent diffusion enhancement ability, ultrasound technology is taken into consideration. Yet there is no literature about HAD of *Flos Lonicerae* with ultrasound application until now.

The aim of this research was to investigate drying characteristics of UHAD of *Flos Lonicerae*. Air-borne ultrasound technology is applied to accelerate HAD process. The influence of ultrasonic radiation distance, ultrasonic power and drying temperature on drying time and drying rate was to be discussed. The effective moisture diffusivity and the activation energy of samples during UHAD were to be calculated.

Materials and methods

Materials

Fresh *Flos Lonicerae* was obtained from a local special plant base of Chinese herbs in the province of Henan, China and was stored in a refrigerator at 2–4 °C. The moisture content of samples was determined in a vacuum

oven at 70 °C for 24 h (AOAC 1990), and the initial moisture content of the samples ranged from 4.62–4.78 (g/g dry base).

Experimental set-up

A schematic of the ultrasound-assisted hot-air dryer is presented in Fig. 1. The dryer was self designed and fabricated by Henan University of Science and Technology. The equipment contains an air regulator, an electric heater, an air blower, a drying chamber, an ultrasonic transducer, an ultrasonic generator, a vibration disk, etc. A material tray is placed in the drying chamber, and the ultrasonic transducer is installed under the tray. A temperature sensor and a velocity sensor, which are fixed closely under the tray, connect a detector to display drying parameter values. The air outside is aerated by the air blower and the flow rate is controlled by the regulator. Then the air flows through the electric heater to obtain thermal energy and the air temperature reaches to a set value. Before the hot air flows through the material tray, ultrasound waves are radiated from the ultrasonic transducer towards the hot air, and the air energy increases.

The air borne power ultrasonic device, which is shown in Fig. 2, is a key component to enhance hot air drying rate. Most ultrasonic transducers are cylinder-shaped or cone-shaped, and easily match solid or liquid mediums and reach high efficiency, mainly due to the great acoustic impedance. The acoustic impedance equation is as following (Morse and Ingard 1968):

$$Z = \rho c \quad (1)$$

Fig. 1 Schematic of ultrasound assisted hot air drying device. 1. air blower 2. electric heater 3. material net tray 4. temperature/velocity detector 5. vibration disk 6. ultrasonic transducer 7. ultrasonic generator

Fig. 2 Air borne power ultrasonic device. 1. tortuous vibration disk 2. amplitude transform rod 3. stainless steel shell 4. wire connector 5. cooling fan

Where Z is the acoustic impedance (N.s/m^3), ρ is the medium density (kg/m^3), c is the sound velocity in the medium (m/s).

Since the values of density and sound velocity of gaseous medium are much smaller than that of liquid medium, its acoustic impedance value is several orders of magnitude smaller than that of liquid medium. So, serious impedance mismatch and low efficiency could be resulted in if the shape of ultrasonic transducer is not redesigned and modified in UHAD process.

Tortuous vibration disk has got considerable attentions in ultrasound application area because of its obvious advantages including low acoustic impedance, large radiation area and high efficiency (Barone and Gallego-Juarez 1972; Gallego-Juarez et al. 2002; Lin 1995). Since tortuous vibration disk has shown significant effects on enforcing HAD of carrot cubes (Fuente-Blance et al. 2006) and mushroom slices (Luo et al. 2013), such kind of ultrasonic transducer is designed, manufactured and applied in this study. The key point for the designing of the disk is that the vibration frequencies of ultrasonic transducer, amplitude transform rod and tortuous vibration disk should be matching. The designed tortuous vibration disk has the parameters of thickness 6 mm and diameter 201 mm. According to measurement results, the testing value of vibration frequency for longitudinal vibrator is 19,937 Hz, the value of vibration frequency for longitudinal vibrator and tortuous vibration disk is 19,975 Hz, and both of the values are close to the theoretical frequency value of 20,000 Hz for ultrasonic transducer. So, the designed ultrasound radiation system could meet designing requirement and be used to provide ultrasound vibration for enhancing HAD rate.

Experimental methods

Buds of ripe *Flos Lonicerae* (3.0–3.5 cm in length) were selected for UHAD experiments. *Flos Lonicerae* of 40 g in weight were uniformly spread on the tray

with load density of 2 kg/m^2 and then put into the drying chamber. UHAD experiments were, therefore, conducted under the conditions of drying temperatures of 40, 50, 60 and 70°C ; ultrasonic radiation distances of 10, 20 and 30 cm; ultrasound powers of 0, 40, 80, 120 and 160 W, respectively. The mass changes of *Flos Lonicerae* samples were measured with an electric balance (Model DJ2000, precision 0.01 g, Zhifu Co., China) and recorded every 20 min. The drying was carried on until constant weight. All experiments were performed in triplicates and the mean values were reported and used for further work.

The moisture content of *Flos Lonicerae* could be calculated through the following equation (Sharma et al. 2005):

$$M = \frac{W - W_d}{W_d} \quad (2)$$

where W is mass of samples (g), W_d mass of dry matter (g), and M moisture content (g/g, dry base).

The drying rate could be calculated as follows (Celma et al. 2009):

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

where M_t and $M_{t+\Delta t}$ are moisture contents at drying times t and $t+\Delta t$, respectively (g/g, dry base).

The dimensionless moisture ratio (MR) could be obtained as follows (Midilli 2001):

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (4)$$

where M_0 is initial moisture content (g/g, dry base) and M_e is equilibrium moisture content (g/g, dry base).

Assuming the main mechanism as being of diffusive nature and treating *Flos Lonicerae* as long cylinders, the experimental data for determination of diffusivity was interpreted by using Fick's second diffusion equation (Crank 1975):

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \left(\frac{\partial M}{\partial r^2} + \frac{1}{r} \frac{\partial M}{\partial r} \right) \quad (5)$$

where D_{eff} is effective moisture diffusivity (m^2/s), t is drying time (s) and r is radius of *Flos Lonicerae* (m).

Thus, the analytical solution of Fick's equation is as follows (Crank 1975):

$$MR = \frac{M - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{4}{\mu_n^2} \exp \left(-\frac{D_{\text{eff}} \mu_n^2 t}{r^2} \right) \quad (6)$$

where μ_n are roots of the Bessel function of the first kind of zero order ($\mu_n = \{2.4048, 5.5201, 8.6537, \dots\}$).

As the M_e value is very small compared to M_0 and M values, the M_e value can be neglected and MR can be expressed as M/M_0 (Goyal et al. 2007). And for long drying time of *Flos Lonicerae* drying with negligible shrinkage, the solution of Fick's equation can be simplified to the first term of the series, with neglecting the higher order term (Doymaz and Pala 2002). Therefore, MR is written in logarithmic form as below (Souraki et al. 2012):

$$\ln MR = \ln \frac{M}{M_0} = \ln \frac{4}{\mu_1^2} - \left(\frac{D_{\text{eff}} \mu_1^2}{r^2} \right) t \quad (7)$$

Effective moisture diffusivity was determined by plotting experimental data in terms of $\ln(MR)$ versus drying time.

The temperature dependence of the effective moisture diffusivity could be described by a simple Arrhenius-type relationship as follows (Baini and Langrish 2007; Celma et al. 2009; Simal et al. 2005):

$$D_{\text{eff}} = D_0 \exp \left(-\frac{E_a}{RT} \right) \quad (8)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a the activation energy (kJ/mol), R the universal gas constant (kJ/mol K), and T the absolute temperature (K).

The activation energy was calculated by plotting the straight line of the natural logarithm of D_{eff} versus the reciprocal of the absolute temperature.

All the statistical calculations were conducted by Origin 8.0 software.

Results and discussion

Drying characteristics

The drying curves and drying rate curves of UHAD at ultrasonic radiation distances of 10, 20 and 30 cm were shown in Figs. 3 and 4. The air velocity, drying temperature and ultrasonic power were set as 1 m/s, 50 °C and 160 W, respectively. The drying time of direct HAD without ultrasound assistance was 340 min. With the application of ultrasound, the drying time was as short as 200 min, and the reduction ratio was 41.2 %. So it is clear that the water removal rate is higher when HAD is assisted by ultrasound. Although the ultrasonic radiation surface does not contact the samples directly, the ultrasonic energy emitted by the ultrasonic radiation board could transmit through the drying medium to reach the surface of the sample. Tens of thousands of vibrations per second produced by the ultrasonic energy strengthen the air current turbulence of the sample surface, reduce the thickness of boundary layer on sample surface, and therefore, improve heat and mass transfer process and decrease moisture diffusion resistance between the sample and drying medium. Moreover, ultrasonic energy penetrates into the samples and causes the "perturbation" effect which could not only expand capillary channels for moisture diffusion and produce microcapillary channels, but also help water molecules inside the samples to overcome the binding force from organizational structure, and accelerate moisture removal

Fig. 3 Drying curves of UHAD of *Flos Lonicerae* with different ultrasonic radiation distances

Fig. 4 Drying rate curves of UHAD of *Flos Lonicerae* with different ultrasonic radiation distances. **a** drying rate Vs drying time **b** drying time Vs moisture content

rate as a result. Garcia-Perez et al. (2012) reported that the reduction in the drying time of 45 % could be achieved with the application of ultrasonic power of 90 W during hot air drying of orange peel slabs, at drying temperature of 40 °C and air velocity of 1 m/s. The decrease of the drying time from 4.4 to 2.5 h was also reported by Gamboa-Santos et al. (2014) during HAD of strawberry at 60 °C and 2 m/s with ultrasonic power of 60 W. Therefore, based on the literature and the data in this experiment, it could be concluded that ultrasound assistance is beneficial to shorten drying time of traditional HAD.

It is referred in Figs. 3 and 4 that the drying times extended to 280 min and 340 min when the ultrasonic radiation distances were 20 cm and 30 cm, respectively, and the corresponding time reduction ratio values were 17.6 % and 0 %. So, it could be implied that the strengthening effects of ultrasound on HAD decrease with the increase in ultrasonic

radiation distance, and vanish when ultrasonic radiation distance is as long as 30 cm. Comparing with the drying rate curves with different ultrasonic radiation distances at ultrasonic power of 160 W, it's obvious that the corresponding drying rate values of UHAD are higher than that of HAD at all moisture contents when ultrasonic radiation is set as 10 cm. When the ultrasonic radiation distance is set as 20 cm, the obvious difference of drying rate between UHAD and traditional HAD could be observed only when the sample's moisture content is above 1 g/g(dry base). At ultrasonic radiation distance of 30 cm, no obvious difference is observed between UHAD and HAD.

Ultrasound energy attenuation equation was introduced as follows (Morse and Ingard 1968).

$$I = I_0 e^{-2\alpha x} \quad (9)$$

where I is acoustic intensity of ultrasound transmitting distance of x (W/cm²), I_0 is initial ultrasound intensity (W/cm²), α is attenuation coefficient (dB/m), x is propagation distance (m).

It could be deduced from Eq. (9) that ultrasound intensity is inversely proportional to ultrasonic propagation distance, and in other words, more ultrasonic energy decay with the longer of ultrasonic radiation distance. Chemat et al. (2011) indicated that the ultrasonic energy attenuation increases significantly with the increase of the ultrasound transmission distance and long ultrasound transmission distance would lead to remarkable reduction of reinforcing effects of ultrasound on mass transfer. Since the loss of ultrasonic energy is low when ultrasonic radiation distance is as short as 10 cm, most of ultrasonic energy could reach the samples and affect both the boundary layer of the sample surface and organization structure and moisture state inside the samples, hence the obvious strengthening effect on drying rate is produced during all the drying process, even when the moisture content is low. With longer ultrasonic radiation distance, such as 20 cm, the attenuation of ultrasonic energy increases and the corresponding strengthening effects of ultrasound on external evaporation process and internal diffusion process descend, the ultrasonic energy arriving at the sample's surface is not great enough to accelerate internal moisture diffusion during the later drying period, in which the moisture content of samples is low and internal diffusion control is primary. When the ultrasonic radiation distance is as long as 30 cm, the ultrasonic energy obtained by the samples is little because of serious energy attenuation during ultrasound transmission, causing negligible influence on drying rate during hot air drying process.

Constant drying rate period was lacked in any of the experiments and entire drying took place in the falling rate period, as shown in Fig. 4. Such a phenomenon indicated that

diffusion is the mechanism governing the moisture removal during HAD of *Flos Loniceræ* with or without applying ultrasound assistance. Two falling rate periods appeared in HAD of *Flos Loniceræ* without ultrasound and with ultrasound assistance at radiation distance of 30 cm, and the transition point existed at drying time of about 125 min, as well as at moisture content of around 1.7 g/g (dry base). Yet the first falling rate period and the second falling rate period were difficult to distinguish and the transition point disappeared when ultrasound was applied at radiation distances of 10 and 20 cm. Therefore, ultrasound application in HAD of *Flos Loniceræ* at suitable distance could strengthen moisture diffusion rate during the second falling rate period as well as the first falling rate period, causing the increase of drying rate and the disappearance of the transition point.

Based on the experimental results and interpretation above, it could be deduced that shortening ultrasonic radiation distance is beneficial to improve both ultrasonic energy efficiency and drying rate. The shorter the ultrasonic radiation distance, the greater the strengthening effect of ultrasound on HAD. Yet because of the limitation of air inlet of the drying equipment, the minimum ultrasonic radiation distance which could be achieved in the study is 10 cm. So, the ultrasonic radiation distance of 10 cm is determined for the subsequent work.

The drying curves and drying rate curves of UHAD with different ultrasonic powers were shown in Figs. 5 and 6. The drying temperature, air velocity and ultrasonic radiation distance were 50 °C, 1 m/s and 10 cm, respectively. The drying time of single HAD was 340 min. Yet when ultrasound was applied to enhance HAD, the drying times reduced to 300, 260, 220 and 200 min, and the corresponding reduction ratios were 11.7 %, 23.5 %, 35.3 % and 41.2 %, at ultrasonic powers 40, 80, 120 and 160 W, respectively. So it's concluded that ultrasound assistance is beneficial to shorten drying time and

Fig. 5 Drying curves of UHAD of *Flos Loniceræ* with different ultrasonic powers

Fig. 6 Drying rate curves of UHAD of *Flos Loniceræ* with different ultrasonic powers. **a** drying rate Vs drying time **b** drying time Vs moisture content

higher ultrasonic power causes shorter drying time. Reductions in the drying time of 35.1 % and 46.1 % were reported by Rodriguez et al. (2014) during drying of apple slabs at 50 °C with two different ultrasonic powers of 45 W and 90 W, respectively.

Only falling rate period was observed in all the experiments, and obvious transition point could not be found when ultrasound assistance was applied, as shown in Fig. 6. It's also illustrated in Fig. 6 that drying rate increased with the increase of ultrasonic power. At the initial phase of drying process of fresh *Flos Loniceræ*, the drying rates of UHAD were 138 %, 165 %, 186 % and 200 % of that of single HAD when the ultrasonic powers were 40, 80, 120 and 160 W, respectively. When the moisture content of samples reduced to half of the initial value, the drying rates of UHAD were 139 %, 171 %, 191 % and 215 % of that of single HAD at ultrasonic powers of 40, 80, 120 and 160 W, respectively. When the moisture

content of samples reached a quarter of the initial value, the drying rates of UHAD were 121 %, 155 %, 185 % and 205 % of that of single HAD at ultrasonic powers of 40, 80, 120 and 160 W, respectively. When the moisture content was as low as 0.5 g/g dry base, the drying rates of UHAD were 110 %, 135 %, 165 % and 195 % of that of single HAD while ultrasonic powers were 40, 80, 120 and 160 W, respectively. Therefore, higher ultrasonic power had more significant effects on drying rate. When the moisture content decreased, the increase ratio of drying rate decreased at low ultrasonic powers whereas the increase ratio remained high values when ultrasonic powers were as high as 120 and 160 W.

Since the attenuation coefficient value in air is much higher than that in liquid, the attenuation rate of ultrasonic energy transmitting in air is obviously quicker than the rate in liquid with the increase of propagation distance. When ultrasonic power is low, most of ultrasonic energy loses when ultrasound transmitted in air to reach the samples, and therefore the radiation effect of ultrasound with low power on samples is limited. Yet when ultrasonic power is as high as 120 and 160 W, although a part of ultrasound energy decayed in transmitting process, quite a number of ultrasound energy could reach the samples and have positive effects on moisture diffusion and evaporation. Such effects were connected with several characteristics of ultrasound including good directivity, big acceleration of medium particles and high vibration frequency. For example, ultrasound waves with frequency of 20 kHz and acoustic intensity of 0.43 W/cm² could impel medium particles to vibrate 20,000 times in 1 s. The maximum acceleration of air particles was 5.03×10^5 m/s², which was much higher than the acceleration value of water particles of 1.44×10^5 m/s², when the same ultrasound waves were applied. Such high vibration frequency and particle acceleration for air were beneficial to improve flow turbulence, reduce

Fig. 7 Drying curves of HAD of *Flos Lonicerae* at different drying temperatures

Fig. 8 Drying curves of UHAD of *Flos Lonicerae* at different drying temperatures

boundary layer and lower water stability, and hence increase mass and heat transfer rates outside and inside the samples.

The drying curves of HAD without ultrasound assistance at different drying temperatures were shown in Fig. 7. The drying times of HAD were 520, 340, 230 and 170 min at the drying temperatures of 40, 50, 60 and 70 °C, respectively, with fixed air velocity of 1 m/s. The increase of drying temperature significantly caused the reduction of drying time, and the result is identical with that in hot air drying which has been reported and illustrated in several literatures (Doymaz 2004; Ihns et al. 2011; Purkayastha et al. 2013). Higher temperature produces larger thermal flux from the drying medium to the samples, enhances water diffusion and evaporation, and improves the drying rate as a result.

The drying curves of UHAD at different drying temperatures were shown in Fig. 8. The applied ultrasonic power was set as 80 W. The drying times of UHAD were 440, 260, 200 and 150 min at ultrasonic power of 80 W when the drying temperatures were 40, 50, 60 and 70 °C, respectively. The drying times with ultrasound assistance were obviously shorter than that of HAD at same temperature. So it could be concluded that not only the temperature, but also ultrasound application affect drying kinetics. Drying time reductions brought about by applying an ultrasonic power of 80 W were 15.4 %, 23.5 %, 13.0 % and 10.5 % when drying temperatures were set at 40, 50, 60 and 70 °C, respectively. So, at higher drying temperatures, the reinforcing effects of ultrasound waves on drying time are obvious, as well as declining. The time reduction values are smaller than the values ranging from 13 to 44 % obtained by Gamboa-Santos et al. (2014) who applied ultrasound to enhance HAD of strawberry at ultrasonic power of 60 W. Garcia-Perez et al. (2012) also reported that drying time reductions of 30 % and 50 % could be achieved in

Fig. 9 Effective moisture diffusivity of *Flos Lonicerae* during UHAD process

UHAD of orange peel slabs with ultrasonic powers of 45 W and 90 W, respectively. The difference observed may be due to the different internal structure of the different samples and different ultrasound assisted hot air drying equipments.

Effective moisture diffusivity

D_{eff} values of *Flos Lonicerae* obtained at different drying temperatures and ultrasonic powers were presented in Fig. 9. D_{eff} values were from 5.05×10^{-11} to 20.33×10^{-11} m²/s, which were within the general range of 10^{-12} m²/s to 10^{-8} m²/s for the drying of food materials (Zogzas et al. 1996). As can be seen in Fig. 9, D_{eff} values increased with the rise in drying temperature at all ultrasonic power levels. When drying temperature rose from 40 to 70 °C, the D_{eff} increases of 237 %, 226 %, 216 %, 206 % and 195 % were observed at ultrasonic powers of 0, 40, 80, 120 and 160 W, respectively. The increase of drying temperature could activate water molecules inside samples, accelerates water transfer and increases water

Fig. 10 Plot of $\ln(D_{\text{eff}})$ versus $1/T$ during UHAD of *Flos Lonicerae*

diffusion as a result. D_{eff} value was considered as a function of drying temperature following an Arrhenius type relationship in several studies (Baini and Langrish 2007; Celma et al. 2009; Gamboa-Santos et al. 2014; Simal et al. 2005).

It is also illustrated that D_{eff} values increased with the rise in ultrasonic power at all drying temperatures. It has been confirmed that the ability of ultrasound could enhance the mass transfer at the interface and inside the products, and improve the D_{eff} values as a result (Ortuño et al. 2010; Ozuna et al. 2011). Compared with the D_{eff} value of HAD at 40 °C, the D_{eff} values of UHAD increased 8.9 %, 16.6 %, 24.3 % and 35.8 % at ultrasonic powers of 40, 80, 120 and 160 W, respectively, and the improvement of D_{eff} was reduced to 5.5 %, 9.6 %, 13.1 % and 19.2 % at 70 °C, which means that the effect of ultrasonic power on D_{eff} values decreases with the increase of drying temperature. Since the large number of thermal energy are available in drying medium at high temperatures, the ratio of ultrasound energy over total energy could almost be negligible (Riera et al. 2011).

Other investigations carried out for other agricultural products during UHAD showed D_{eff} values to lie between 1.87 and 11.60×10^{-10} m²/s for apple (Rodriguez et al. 2014); 0.763 and 2.293×10^{-10} m²/s for strawberry (Gamboa-Santos et al. 2014); 2.39 and 5.99×10^{-10} m²/s for persimmon (Carcel et al. 2007); 3.42 and 4.13×10^{-9} m²/s for lemon peel (Garcia-Perez et al. 2007); 1.82 and 2.28×10^{-9} m²/s for mushroom, 0.46 and 1.14×10^{-9} m²/s for Brussels sprouts, and 1.07 and 2.05×10^{-9} m²/s for cauliflower (Jambrak et al. 2007).

The activation energy values were determined by plotting $\ln D_{\text{eff}}$ versus $1/T$ as shown in Fig. 10. The calculated value of activation energy for HAD of *Flos Lonicerae* without ultrasound assistance was 36.05 kJ/mol. The activation energy values obtained decreased to 34.28, 32.59, 30.36 and 28.90 kJ/mol for the assays carried out at ultrasonic powers of 40, 80, 120 and 160 W, respectively, and the corresponding reduction ratio values were 4.9 %, 9.6 %, 15.8 % and 19.8 % compared with the activation energy value of HAD. Therefore, the activation energy values decreased significantly with the increase of ultrasonic power, which was consistent to the report of Gamboa-Santos et al. (2014).

Conclusions

The experiments of UHAD of *Flos Lonicerae* were conducted. The influence of ultrasound on drying rate of HAD decreases with the increase in ultrasonic radiation distance because of energy attenuation during ultrasound transmission. The increases in ultrasonic power and drying temperature improve drying rate significantly. The effects of ultrasonic radiation distance and ultrasonic power on drying rate

decrease with the reduction of samples' moisture content during drying process. D_{eff} values were from 5.05×10^{-11} to $20.33 \times 10^{-11} \text{ m}^2/\text{s}$ in UHAD of *Flos Lonicerae*, and increased with the increase in drying temperature and ultrasonic power. The calculated values of activation energy were 36.05, 34.28, 32.59, 30.36 and 28.90 kJ/mol for the assays carried out at ultrasonic powers of 0, 40, 80, 120 and 160 W, respectively. Therefore, it is concluded that ultrasound application significantly affects HAD process, and is beneficial to shorten drying time and increase drying rate of traditional HAD process.

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