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Study of Effective Moisture Diffusivity of Oak Acorn

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***Abstract*—**The purpose of present work was to study the drying kinetics of whole acorn and its kernel at different drying air temperatures and their effective moisture diffusivity. The results indicated that the drying time of whole acorn was 442, 206 and 188 min at the air temperature of 65, 75 and 85ºC, respectively. At the same temperatures, the drying time of kernel was 131, 56 and 76min. The results showed that the effect of drying air temperature increasing on the drying time reduction could not be significant on acorn drying at all conditions. The effective moisture diffusivity of whole acorn and kernel increased with increasing air temperature from 65 to 75ºC. However more air temperature increasing, led to decreasing this property of acorn kernel. The critical temperature of acorn drying was about 75°C in which acorn kernel had the highest effective moisture diffusivity.

***Keywords*—**Critical temperature, Drying kinetics, Moisture diffusivity, Oak acorn.

I. Introduction

OAK acorn consists of the kernel (70%), shell, tannin and etc (30%). Acorn is rich in fat, fiber, calcium and its protein and fat value are about half and 3-4 times of wheat and barley's, respectively. It has many medicinal properties and uses extremely in the traditional medicine. Acorn flour is used to treat hemorrhoid, digestive problems and burns. Acorn is an excellent source of tannin which mostly exists in the shell. Tannin uses in dyeing, seine protection, oil refining, metallurgy and etc.

The majority trees of Iran's Zagros forests are oak, Q. brantivar persica accessions, with over than 10 million tones annual acorn production. Such high production makes it necessary to study acorn postharvest processing such as drying and extraction of acorn flour or tannin. Acorn has high metabolic activity because of its high moisture content (40% w.b.), which makes its storage difficult. Industrial production of acorn flour needs to separate their shell and kernel. It is obvious that the shelling operation of acorn needs high energy because of the high moisture content and adhesion between the shell and kernel. Acorn drying is one of the alternative methods to possible the shelling operation and reduced shelling energy requirements and could improve the storage quality over an extended period. So drying is the simplest methods to achieve these purposes. The most common drying method is open air-sun drying, which is used for vegetables and fruits [1]. However the high production level of acorn limits the sun drying usages and necessitates the application of industrial dryers. Industrial dryer designing needs to study and evaluation of drying kinetics and the effect of drying parameters on the dryer performance.

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A complete drying kinetic consists of two stages: a constant-rate followed by a falling-rate of drying period. The drying of most hygroscopic porous materials started from the falling-rate period and no constant rate of drying is observed. The mechanism of moisture movement within these materials during the falling-rate period could be represented by a diffusion phenomenon [2]. The effective moisture diffusivity of food stuff could obtain from the drying kinetics and dependences on the material temperature. Considering the sample temperature reaches to the drying air temperature at a few minutes, the effective moisture diffusivity obeys Arrhenius relationship that expresses as a function of drying air temperature [2]-[4]. In addition, there is a need for qualitative and quantitative understanding of the heat and moisture transfer mechanisms in the drying process. This is important for the development of new dried food, for more economical and efficient processing of foods, and for better dried food quality and safety. If the mechanism of a process is well understood, mathematical models can be developed to present the process. Experiments can virtually be carried out on the mathematical models under broad experimental conditions in an economical and timesaving manner. With process models, quantitative calculations and predictions can be made for more reliable design, optimization of design and operating condition, and evaluation of process performance [5].

This research is part of a study on the acorn processing including of drying, shelling, modeling of these operations as well as designing the suitable process and equipments.

The aim of this study was to obtain the drying kinetics of whole acorn and its kernel (shelled acorn) and to estimate the effective moisture diffusivity from the drying data. This method could make acorn processing more economical and reduce the energy consumption.

II. Materials and Methods

In order to study the drying process of acorns, the samples were obtained from Zagros forests in the west region of Iran and stored at 4°C until use. The initial moisture content of both whole acorn and kernel was determined in a mechanical convection oven at 70±1°C, until a constant weight was attained [6]. The initial moisture content of whole acorn and its kernel was 0.695 and 0.666 g_{water}/g_{solid} (41% and 40% w.b.), respectively.

Acorn drying was conducted at two phase: whole acorn drying and kernel drying. In order to kernel drying, the shell of whole acorn was removed manually. The shell thickness was about 2.5mm and it consisted of a dense and hard structure. The experiments started after 2h of equilibrium of sample to the ambient temperature.

Drying was performed in a pilot plant tray-dryer. The dryer mainly consists of three basic units; (1) a fan providing desired drying air velocity, (2) electrical heaters controlling the temperature of drying air and drying chamber, and (3) a weighting system measuring the weight of samples. The velocity of air flow was controlled by changing the rotating speed of fan (SPC1-35, Autonics, Taiwan) and measured using a vane probe type anemometer (AM-4202, Lutron, Taiwan) with an accuracy of ±0.1 m/s. Air was heated, while flowing through three spiral type electrical heaters, having 5, 5 and 2 kW capacity. Weighing system consisted of an electronic balance (AND GF3000, Japan) having an accuracy of 0.01 g and the weight of samples were recorded on a PC [1].

Whole acorn and kernel were used to obtain the drying kinetics. The drying air temperature was 65, 75 and 85°C and air velocity was 1.5m/s. Each experiment was repeated two times. When the dryer achieved a steady state condition, acorn samples (100g) were put on the tray that was connected to a balance. Weight loss of samples was measured every minute by the balance.

The both of whole acorn and kernel were assumed as a long circular cylinder and their effective moisture diffusivity was calculated by plotting experimental drying data in terms of Ln(W) versus time. Where W is the dimensionless moisture content [2].

The effective moisture diffusivity dependences on the air temperature and express by the Arrhenius relationship (1);

$$D_{eff} = D_0 \exp\left(-\frac{Ea}{R\,T}\right) \tag{1}$$

where Ea is the activation energy (J/mol), R is the universal gas constant (8.3143 J/(mol.K)), T is air absolute temperature (K) and D_0 is the pre-exponential factor of Arrhenius equation (m^2/s).

Correlation of the experimental effective moisture diffusivity with this relationship was evaluated by MATLAB software and the coefficient of determination (R^2) was used as criteria for verifying the goodness of fit.

A series model was used to estimate the effective moisture diffusivity of acorn shell [2] and expressed by the following equation:

$$D_{sh} = \frac{\varepsilon_{sh}}{\left(1/D_w\right) - \left(\varepsilon_k/D_k\right)} \tag{2}$$

where D_w, D_{sh} and D_k were the effective moisture diffusivity of whole acorn, shell and kernel (m^2/s), respectively. ε_k and ε_{sh} were volume fractions of kernel and shell, respectively and obtained from the following equations:

$$\varepsilon_k = \frac{V_k}{V_w} \tag{3}$$

$$\varepsilon_{sh} = 1 - \varepsilon_k \tag{4}$$

V_k and V_w were the volume of whole acorn and kernel (m^3) that were measured by the toluene displacement method [7].

III. Results And Discussion

The moisture content versus drying time at air temperature of 65, 75 and 85°C and constant air velocity (1.5m/s) for both of whole acorn and kernel is shown in Fig. 1.

As expected increasing the air temperature from 65 to 75°C led to decrease the drying time of whole acorn from 442 to 206min, when the moisture content fell to 0.394 g_{water}/g_{solid} (28.2% w.b.). However more air temperature increasing from 75 to 85°C had little effect on the drying time, so that it decreased from 206 to 188min. The ANOVA results showed that the increasing of drying air temperature on the drying time reduction is significant.

The drying time of acorn kernel was 131, 56 and 76min (Fig. 1), at the air temperature of 65, 75, 85°C when the moisture content reached to 0.374 g_{water}/g_{solid} (27.2 % w.b.). The drying time at 85°C was longer than 75°C that was unpredictable. These results showed that the critical drying temperature of acorn kernel is about 75°C in which increasing the drying air temperature had the adverse effect on the drying process.

Koyuncu et al. [8] studied the drying of chestnut at different air temperatures and velocities. The drying time of samples at the drying air temperatures of 40, 50, 60 and 70°C was 212, 67, 53 and 47 hr. They reported that there is the highest difference between the drying time at the air temperature of 40 and 50°C and the differences between other temperatures from viewpoint of drying time were lower. So there is a critical drying temperature (50°C) in chestnut drying. They also reported that the air velocity had no significant effect on the drying time of samples.

The direct effect of air temperature increasing on the drying time reduction had also reported by Guine and Fernandes [9] for chestnut verities. Also for most materials, it has reported that the drying time decreased as the air temperature increased [1]-[4], [10]-[14].

Fig. 2 represents the variation of drying rate with the moisture content at various air temperatures. A long with drying development and reduction of moisture content, the drying rate of samples decreased. The curves show that there is no constant drying rate and the drying process occurs in the falling rate period. The lowest drying rate of both whole acorn and kernel was at the 65°C.

Guine and Fernandes [9] showed that when the temperature increased from 70 to 80°C, the drying rate of chestnut increased at early stages but at the final stage the drying rate was stabilizing. This indicated that the effect of air temperature was negligible at lower moisture content. Similar results reported during drying of fruits and vegetables such as apple, figs and apple [1], [15] and [10], respectively..

It is obvious from the curves that the drying rate of whole acorn continued to increase as the air temperature increased. The same trend was observed for acorn kernel when the air temperature increased from 65 to 75°C. Nevertheless more air temperature growing had adverse effect on the drying rate of acorn kernel, so that at air temperature of 85°C, it was lower than that of at 75°C.

These results are in contrast with most previous researches. Chemical and structural changes due to the high temperature could describe these results will be discussed at the next section.

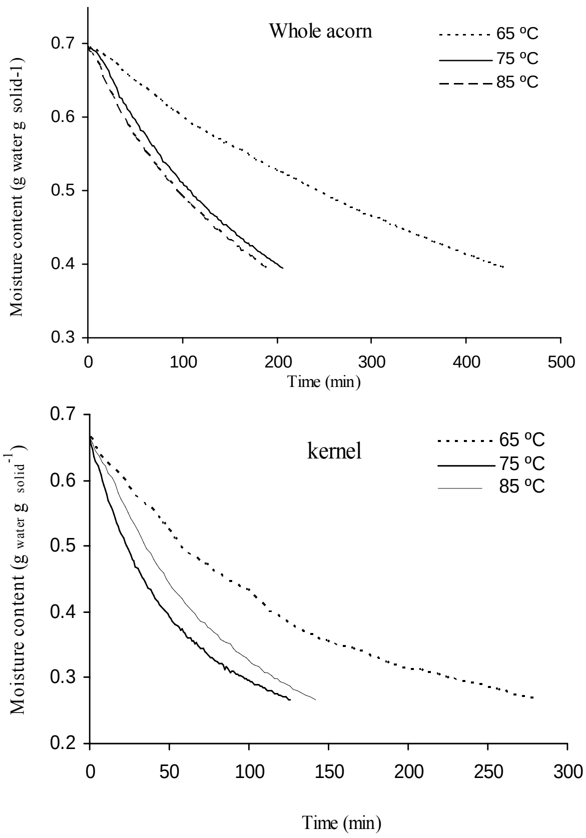

Fig. 1 Drying curves of whole acorn and kernel at different air temperatures

In addition at all air temperature, the drying time and rate of whole acorn was longer and higher than those of kernel (Fig. 3). This is due to this fact that acorn shell as a natural barrier restricts the moisture diffusion. The same results were found by Biju Cletus and Carson [16]. They observed that the drying rate of New Zealand chestnut without both shell and pellicle was the highest. The samples with pellicle only and with both shell and pellicle were in the lower levels. Also they reported that the drying rate increased as the air temperature increased.

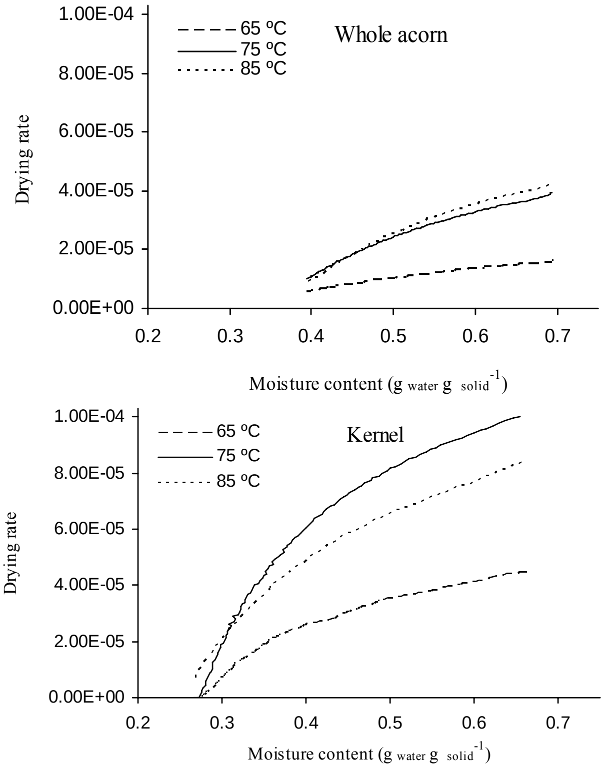

Fig. 2 Drying rate vs. moisture content of whole acorn and kernel at different air temperatures

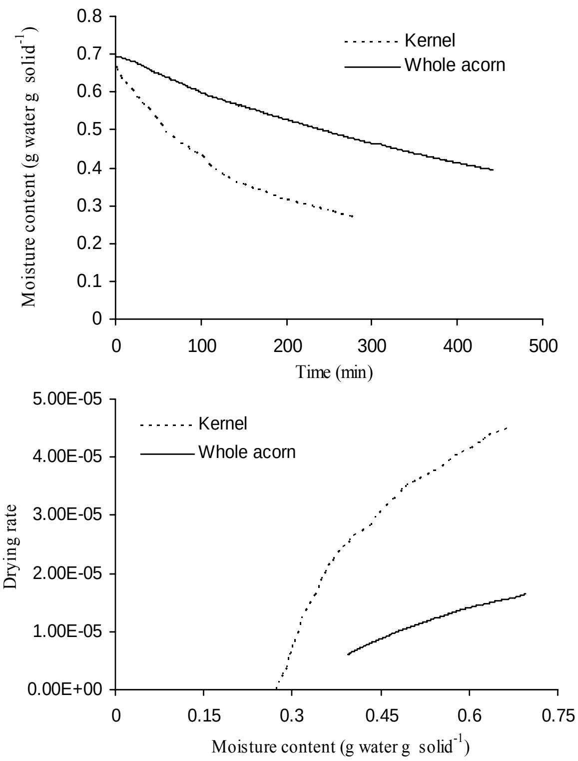

Fig. 3 Drying rate and drying time of whole acorn and kernel at air temperature of 65 ºC

The volume of whole acorn and kernel was measured about 6.95 and 4.93cm^3, respectively. The volume fraction of kernel and shell (ε_k and ε_{sh}) were obtained about 0.725 and 0.275, respectively. The effective moisture diffusivity of kernel and whole acorn were calculated from (1). These values were used to calculate the effective moisture diffusivity of shell based on (2) and represented in Table I.

The effective moisture diffusivity of whole acorn and kernel increased from 2.26 10^{-10} to 4.94 10^{-10} and 5.087 10^{-10} to 11.571 10^{-10} m^2/s, respectively with increasing air temperature from 65 to 75°C. But more air temperature increasing from 75ºC, led to decreasing this property of acorn kernel and had no significant on this property of whole acorn. These results indicated that the effective moisture diffusivity of whole acorn and kernel did not obey Arrhenius relationship at all studied drying air temperature. Fitting Arrhenius relationship to the experimental data had low coefficient of determination that shown at Table II. However, at the air temperature of 65ºC to 75ºC, the Arrhenius relationship could be used to express the changes of the effective moisture diffusivity.

TABLE I
THE EFFECTIVE MOISTURE DIFFUSIVITY OF WHOLE ACORN, KERNEL AND SHELL AT DIFFERENT AIR TEMPERATURES

Effective moisture diffusivity (m^2/s)			
Air temperature (ºC)	Whole acorn	Kernel	Shell
65	2.26 10^{-10}	5.087 10^{-10}	0.917 10^{-10}
75	4.94 10^{-10}	11.571 10^{-10}	1.97 10^{-10}
85	5.13 10^{-10}	9.585 10^{-10}	2.31 10^{-10}

TABLE II
FITTING ARRHENIUS RELATIONSHIP TO THE EXPERIMENTAL DATA

	Arrhenius relationship	R^2
Whole acorn	$D_{eff} = 9\,10^{-9} \exp\left(-\frac{1945.54}{R.T}\right)$	0.845
Kernel	$D_{eff} = 10.21\,10^{-9} \exp\left(-\frac{1545.55}{R.T}\right)$	0.61

Guine and Fernandes [9] calculated the effective moisture diffusivity of chestnut varieties according to Fick's second low by assumed the chestnut as a sphere. It increased linearly from 4.45 10^{-9} to 5.4 10^{-9} and 6.87 10^{-9} m^2/s as the air temperature grew from 70 to 80 and 90ºC, respectively. On the other hand many researchers reported that the effective moisture diffusivity is temperature dependent and obeys Arrhenius relationship. According to this relationship, as the air temperature increases, the effective moisture diffusivity of food stuff increases [2], [3], [4], [17], and [18].

According to the results the critical temperature of acorn kernel drying is about 75 °C in which acorn it had the highest effective moisture diffusivity and there is no reason to use the high air temperature above 75ºC in drying process. These phenomena can be explained by:

(1) When the air temperature increased more than 75°C, the surface structure of kernel changed due to the heat effect. This crust had the same rule of external shell and restricted the diffusion of internal moisture to the outside. So it limited the effect of the temperature increasing on the effective moisture diffusivity of kernel.
(2) Along with air temperature increasing, some chemical changes occurred in kernel structure and affected its effective moisture diffusivity.

So the most important factor on the effective moisture diffusivity decreasing can be the some chemicophysical variation occurred in the acorn structure.

At all conditions the effective moisture diffusivity of kernel was higher than whole acorn, and the acorn shell had the lowest moisture diffusivity (Fig. 4). At the drying air temperature of 65°C, the difference between the effective moisture diffusivity of whole acorn and kernel was 2.83 10^{-10} m^2/s. It may duo to the low effective moisture diffusivity of shell that calculated according to the series method. It indicates that the shell might restrict the diffusion of internal moisture in the samples to the outside, so had a significant effect on the effective moisture diffusivity of whole acorn. During whole acorn drying, acorn kernel shrinkage was higher than that of shell. It caused a space forms between shell and kernel that fills by air. Considering that the air thermal diffusivity is lower than that of food stuff, as a heat resistance limits the heat transfer and reduces the effective moisture diffusivity of whole acorn. On the other hand, chemical changes in the acorn kernel structure due to the high air temperatures (more than 75ºC) led to decreasing the effective moisture diffusivity of acorn kernel. In spite of the adverse effect of chemical changes and air layer on the effective moisture diffusivity of whole acorn, the positive effect of air temperature causes little growing of this property. Biju Cletus and Carson [16] showed that the effective moisture diffusivity of whole chestnut and chestnut without both shell and pellicle at 30ºC was 5.1 10^{-11} and 9.7 10^{-11}m^2/s, respectively. As a view point of energy efficiency, drying of acorn kernel is more economical because it has the high effective moisture diffusivity (5.087 10^{-10} at 65ºC) compared with whole acorn (2.26 10^{-10} at 65ºC) as well as the activation energy of kernel (1545.55 KJ/mol) were lower than whole acorn (1945.54 KJ/mol). So it is suggested that the shelling operation be done before complete whole acorn drying.

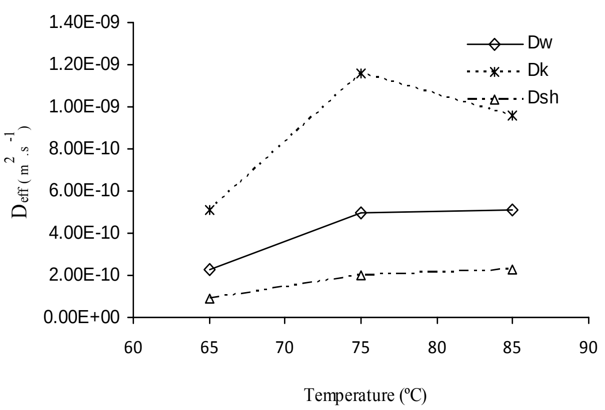

Fig. 4 The effective moisture diffusivity of whole acorn, kernel and shell; Dw, Dk and Dsh, respectively; at different air temperatures

CONCLUSION

In spite of most previous researches on different products, according to the results of this study, the effect of drying air temperature increasing on the drying time reduction could not be significant on acorn drying at all drying conditions. The drying air temperature increasing from about 75ºC had adverse effect on the effective moisture diffusivity of acorn obeys Arrhenius relationship just below the 75ºC. It is not logical to use high drying air temperature because it decreases the effective moisture diffusivity and increases the drying time. In order to design the acorn process pattern, it is recommended to use the low step of the drying air temperature so that the critical temperature obtains with high accuracy, measuring the shrinkage of whole acorn and acorn kernel, study shelling process at different moisture content so that the energy requirements define. By such information, the acorn process could conduct at high energy efficiency. The chemical variation of acorn structure must be studied during the drying process to obtain the effect of drying air temperature. Such variation could affect the drying condition significantly.

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