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Physical Properties in Drying of Food Products with Combined Sublimation and Evaporation

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Abstract Drying is an important unit operation in processing of biological resources. The drying process may influence the product properties and quality, which may shrink, break or undergo rheological, physical and biochemical changes. The important parameters responsible for such changes are drying conditions, type of drying technology and residence drying time. Thermal conductivity, thermal-mass diffusivity, enthalpy, porosity and density are the main material property and heat-mass transfer parameters, which are essential for understanding the changes in product quality and for designing and dimensioning the drying processes. In this paper physical properties of food products undergoing a combined sublimation and evaporation were studied. Pieces of vegetables and potatoes were dried in a heat pump fluidized bed dryer at combined modes with temperatures below the freezing point in the beginning and a final drying step at temperatures above the freezing point. Samples of products were tested at different moisture contents with respect to physical properties. Physical properties of leek and potato samples were measured and mass diffusivities were determined from drying kinetic data. Based on bulk density and rehydration measurements it was clearly observed that drying temperature and modes influenced the final product physical properties. The potato cube run dried with initial atmospheric freeze-drying step had rehydration ability 430% above a run dried only above the freezing point. The average effective mass diffusivity for 5 mm slabs of leek was $0.5\times10^{-11}\mathrm{m^2\cdot s^{-1}}$ for the sublimation stage and $2.2\times10^{-11}\mathrm{m^2\cdot s^{-1}}$ for the evaporation stage.
Keywords physical properties, dying, food products, sublimation, evaporation

1 INTRODUCTION

Heat pump dryers are attractive for the processing of heat sensitive materials since the drying conditions are easily controlled as described by Alves-Filho and Strømmen[1]. Aside from being able to save energy this dryer design is based upon an environmentally friendly technology. In Norway it has been applied industrially for the drying of fish and apples. The additional successfully dried products are fish, fish residues, fruits, vegetables, dairy, biological and other active or heat sensitive materials. The drying modes allow controlling the drying chamber inlet conditions and implies high final product quality. Claussen[2], Bøhn[3] and Alves-Filho and Strømmen[4] performed several tests and determined the dried samples quality and properties based on measured porosity, density, rehydration, color, hardness and other properties.

Heat pump fluidized bed dryers are now being industrialized and used for drying of different types of vegetable products. To ensure industrial success of those plants more data is needed on fundamentals of drying by combined sublimation and evaporation.

In this work drying experiments of vegetables were performed in a combined sublimation and evaporation mode in the heat pump fluidized bed dryer. Vegetables were prepared and dried in a heat pump fluidized bed dryer at temperatures below and above the freezing point. Different conditions and moisture contents were used to study possible effects on physical properties and quality. The mass effective diffusivities were determined from drying kinetics data obtained for leek and potato. Measurements on bulk density and rehydration indicated that drying temperatures and residence time influence the final product physical properties.

2 MATERIALS AND METHODS

A schematic layout of a heat pump fluidized bed dryer used in the experiments shown in Fig. 1. Detailed description of heat pump dryers (HPD) is given by Alves-Filho and Strømmen (1996). The HPD main components are the blower, drying chamber, cyclone, compressor, evaporator, condensers, valves and connections.

The main advantages of the heat pump dryers are as follows:

(1) A low energy consumption due to a high specific moisture extraction rate (*SMER*). The *SMER* is typical in the order of 2 kg to 5 kg of water per kW·h depending upon the drying temperature and is expressed as:

$$SMER = COP\frac{\Delta x}{\Delta h} \tag{1}$$

(2) An operation with coefficient of performance

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(*COP*) as high as possible, computed by the following equation:

$$COP = \frac{Q_0}{W} \tag{2}$$

(3) The drying conditions can be regulated with drying temperature ranges from −20℃ to 110℃. Quality parameters of the product can be controlled due to the low temperatures and the possibility for partly freeze-drying.

(4) The technology is environmentally friendly due to the re-circulation of the drying air and the high thermal efficiency of the dryer.

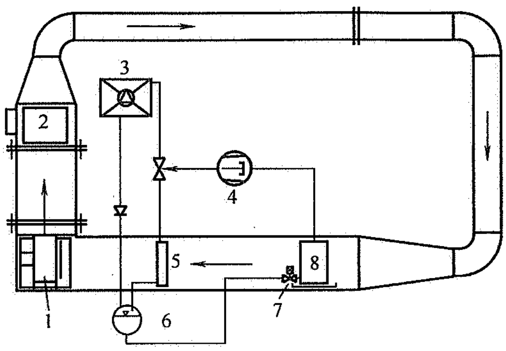

Figure 1 Heat pump fluidized bed dryer
1—fan; 2—drying chamber; 3—condenser 2; 4—compressor; 5—condenser 1; 6—receiver; 7—throttle valve; 8—evaporator

The raw materials used in the experiments were leek and potato samples. The leek was cut into slabs of 5 mm×5 mm, 10 mm×10 mm and 20 mm×20 mm and dried at −5℃ and 25℃ in the experimental heat pump fluidized bed dryer. The sorption isotherms were measured in Aqua Lab CX-2 water activity meter.

To study the drying mechanisms of leek each slab was separated and cut in three different parts, as illustrated in Fig. 2. The drying curves were obtained for each leek slab drying experiments using the recorded drying time and the measurements of moisture content for the whole batch and for each slab part in specific time intervals.

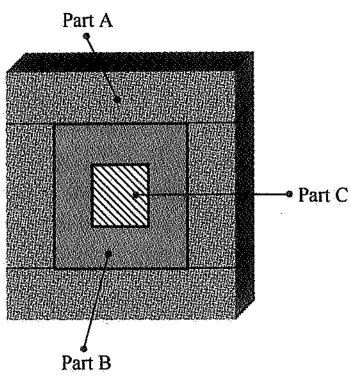

Figure 2 Selected regions for cutting the leek slabs

The potato varieties were Pimpernel, Beate and Mandel that were cut into cubes with side size of 5 mm. The bulk density and rehydration index were measured based on the boiling time before drying by sublimation and evaporation.

3 THE EFFECTIVE MASS DIFFUSIVITY OF LEEK SLABS

The background for the choice of the drying kinetics model was based on observations made in preliminary drying tests, which showed that the leek slabs presented higher water removal rates in the edges than in the center, which is consistent with the present results. The effective mass diffusivity was described using a two-dimensional flat plate Fick's model, as shown in Fig. 3.

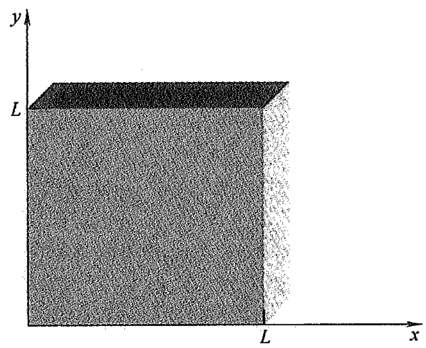

Figure 3 The two-dimensional leek slab for the Fick's model

In that case the Fick's law solution may be expressed using the following equation:

$$\ln\left[\frac{(X - X_e)A_t}{X_o - X_e}\right] = \ln\left(\frac{16}{\pi^2}\right) \cdot \left(-2\frac{\pi^2}{L^2}D_e t\right) \cdot \ln(A_{ed}) \tag{3}$$

where

$$A_{ed} = 2.2586 \cdot 10^{-6}\frac{L^2}{\pi^2} \tag{4}$$

4 RESULTS

4.1 Drying curves

The drying curves for the different parts of 20 by 20 mm leek slabs are presented in Fig. 4. The moisture difference between the slab edge and center is high during the whole drying interval with maximum moisture difference of about 20%(wet basis) at 30 hours of drying. Then that difference reduces to about 12%(wet basis) at the end of drying, in which the edge reaches 6%(wet basis) and the center 18%(wet basis). This indicates that the drying rate is much higher for the slab edge and lower for the slab center. Therefore, regions of the leek may be pre-selected, cut and dried according desired length of residence time.

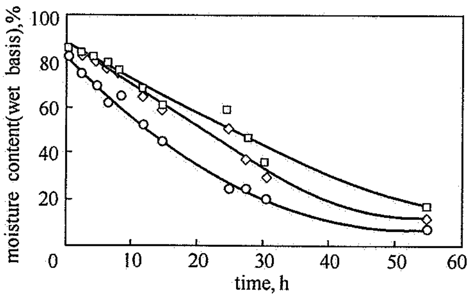

Figure 4 Drying curves for different part of leek slabs dried at 25℃
○ Part A; ◇ Part B; □ Part C

4.2 Sorption isotherms

The sorption isotherms for the different parts of the 20 mm leek slab are presented in Fig. 5. It is observed that for three parts of the leek slab the water activity rises sharply from 0.28 at moisture content wet basis of 6.9% to 0.69 at moisture content of 23.5% and then it rises slower towards the unit at about 88%. Yet, it seems that the sorption isotherms overlaps for the whole range of moisture content between 8 and 88%. Therefore, no clear differences were detected between equilibrium moisture content and water activity for the different regions of the leek slab. Nevertheless, further and more detailed tests must be done to verify that result.

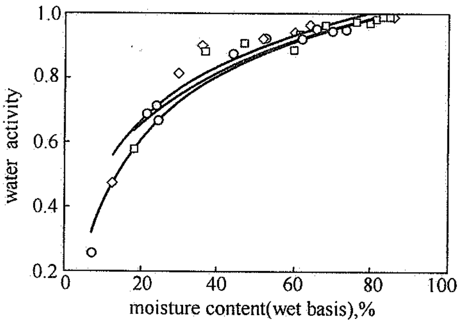

Figure 5 Sorption isotherm at 25℃ for different parts of the leek slab
○ Part A; ◇ Part B; □ Part C

4.3 Effective mass diffusivity

The effective mass diffusivity for 5 mm and 10 mm leek slabs dried at −5℃ and 25℃ is shown in Fig. 6. It indicates that the effective mass diffusivity increases with the moisture content and for smaller sample size.

Consistently, the D_e rises abruptly with the moisture content for the 5 mm slab while it rises slowly for 10 mm slab, both dried at 25°C. Also, it indicates the D_e is much higher for leek runs dried at 25℃ than at −5℃. The average D_e for 5 mm leek slabs was $0.5 \times 10^{-11}\,\mathrm{m^2{\cdot}s^{-1}}$ for the sublimation and $2.2 \times 10^{-11}\,\mathrm{m^2{\cdot}s^{-1}}$ for the evaporation stage.

However, the data for low temperature dried leek shows opposite effect of slab size, in which D_e is lower for the 5 mm than for the 10mm slab. However, additional low temperature drying tests of leek is needed to study the effect of slab size on effective mass diffusivity.

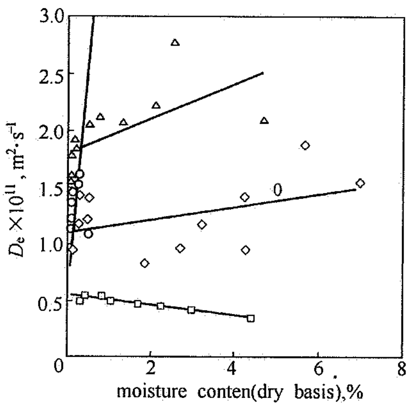

Figure 6 Effective mass diffusivity for 5 and 10 mm leek slabs dried at −5℃ and 25℃
◇ s/t: 10/ − 5; □ s/t: 5/ − 5; △ s/t: 10/ + 25; ○ s/t: 5/ + 25

4.4 Rehydration index

The rehydration index for a given time interval, is defined as the ratio of the wetted sample (by mass) to the dried sample (by mass), which is expressed as follows:

$$R = \frac{M_f}{M_p} \tag{5}$$

Data were obtained and in according to Eq. (5) the rehydration was determined for potato cubes boiled with different times, with different residence times at low temperature. The drying was done at −5℃ and 25℃ and the results are presented in Table 1. The rehydration index is directly proportional to the preboiling time and varies inversely with the drying time at low temperatures, within the range studied. Rehydration is high for all runs and with minimum and maximum values of 430% and 580% for the potato samples pre-boiled for 8 and 15 minutes and dried at low temperature for 5 and 6 hours, respectively. The intermediate rehydration value is 560% for the potato run preboiled for 15 minutes and dried at low temperature 5 hours.

Table 1 Rehydration for potato cubes with different boiling times and drying modes

Potato variety	Boiling time, min	Drying time at −5/20℃, h	Bulk density kg·m^{-3}	Rehydration index
beate	15	6/2.5	150	5.8
pimpernel	15	5/2.5	161	5.6
mandel	8	5/2.5	176	4.3

4.5 Bulk density

The bulk density is determined by standard methods and is defined as total mass of the dried samples and the voids between particles, per volume. The density was determined for all potato cubic samples. It affected by the boiling time and the residence time at low temperature. As shown in Table 1 the bulk density is varies inversely with both the pre-boiling time and drying time at $-5°C/20°C$. All dried samples presented low density with minimum and maximum values of $150\,kg{\cdot}m^{-3}$ and $176\,kg{\cdot}m^{-3}$ for the samples pre-boiled for 15 min and 8 min and dried at low temperature for 6 and 5 h, respectively. The potato run pre-boiled for 15 minutes and dried at low temperature for 5 hours presented and intermediate bulk density of $161\,kg{\cdot}m^{-3}$.

5 CONCLUSIONS

Several vegetable experimental runs were done at different pre-processing and drying conditions. The drying curves and relevant physical properties such as isotherm, effective mass diffusivity, bulk density and rehydration were studied.

The drying curves were obtained for the different parts of the leek slabs. The results show that the drying rate is higher for the slab edge than the center and that regions of the leek may be selected, cut and dried according pre-specified residence time.

Isotherms were determined for the three different parts of the leek slab. The water activity slope rises sharply at lower moisture content and later it rises slower to unit. The data indicates that the isotherms overlap for all runs, with no clear difference for any of the parts studied implying that further tests are needed for to verify that data.

The effective mass diffusivity rises with the drying temperature. It also increases with moisture content and smaller size slab if dried at 25℃. Yet, the data for low temperature dried leek shows opposite effect and more tests to study the effect of slab size on effective mass diffusivity.

The potato rehydration varies directly proportional to the pre-boiling time and inversely with the drying time at low temperatures, within the range studied. It is high for all runs and with minimum and maximum values of 430% and 580% for runs pre-boiled for 8 and 15 minutes and dried at low temperature for 5 and 6 hours, respectively.

The potato density was determined based on boiling and residence times. It varies inversely with both the pre-boiling time and drying time at $-5°C/20°C$. All runs had low densities in the range of $150\,kg{\cdot}m^{-3}$ and $176\,kg{\cdot}m^{-3}$ for runs pre-boiled for 15 and 8 minutes and dried at low temperature for 6 and 5 hours, respectively.

The heat pump fluidized drying at low temperatures with combined sublimation and evaporation produced a final product with low bulk densities and high rehydration index. Also, the dried vegetables were well suited for the instant food products market.

NOMENCLATURE

A, B, C	leek slab edge, middle and central parts
A_{ed}	surface area of edges, m^2
A_t	total surface area of the slab, m^2
D_e	effective mass diffusivity, $m^2{\cdot}s^{-1}$
HPD	heat pump dryer
L	leek slab side length, m
M_f	wetted sample mass, kg
M_p	dried sample mass, kg
Q_o	refrigeration capacity, kW
R	rehydration index, decimal
$SMER$	specific moisture extraction rate, kg water/kW·h
t	time, s
X	moisture content, decimal db
X_e	equilibrium moisture content, decimal db
X_0	critical moisture content, decimal db
W	energy consumption, kW

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